II CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
II NATIONAL CONGRESS OF MECHANICAL ENGINEERING
12 a 16 de Agosto de 2002 - João Pessoa – PB

DETECTION OF OIL VISCOSITY VARIATION IN A GEARBOX BY VIBRATION ANALYSIS

Rui Gomes Teixeira de Almeida
Universidade de São Paulo - Escola Politécnica – Depto. de Engenharia Mecânica
rui.almeida@poli.usp.br

Linilson Rodrigues Padovese
Universidade de São Paulo - Escola Politécnica – Depto. de Engenharia Mecânica
lrpadove@usp.br

Abstract: *The major physic characteristic of a lubricant is its viscosity. This property can be altered by chemical or mechanical degradation, contamination with water or other products. This work presents a study of the detection of lubricant viscosity alteration in gearbox by vibration analysis. Vertical and axial vibration data were acquired from an experimental apparatus consisting of a gearbox with spur teeth. The experiment was performed using lubricant oils (without additives) with different viscosities, and considering several shaft speeds. The temperature of the lubricant was also monitored. Collected data were analyzed using some well-known signal processing and statistical methods as well as a proposed new one. The results show that it is possible to use vibration signals to clearly detected and classify lubricant viscosity variation.*

Key-words: *predictive maintenance, vibration, signal processing, lubrication, gearbox.*

1. INTRODUCTION

Predictive maintenance has been used over last few years as an important strategy to improve industrial plant reliability. Furthermore the improved maintenance systems can increase industrial profits since, in general, the maintenance effective cost is smaller than that of production losses due to non-programmed stops in industrial plants.

Good lubrication in rotating machinery is an important way to improve equipment durability and reliability, two important qualities to be taking into account in any efficient maintenance strategy. The usual procedure to evaluate equipment lubrication condition in industrial plants is oil analysis that comprehends determining physical and chemical characteristic, as well as the presence of wear particles, in pre-collected samples.

Particularly in gearbox lubrication case, if a failure lubrication occurs, metal-to-metal contact will happen, causing wear damages and oil contamination. Despite of the oil expulsion from the contact, during teeth contact time, a small oil film can be kept at contact interface, and the lubrication condition is satisfactory. Different oil viscosities can lead to differences in the way that oil is expelled.

The use of vibration analysis in monitoring and diagnosis of lubrication condition in gearbox and rotating machinery brings some advantages to the problem, that is the increasing of equipment reliability, since the acquisition and the data analysis can be performed in the plant in real time. In this manner incipient failures of lubrication conditions can be detected earlier what allow a faster performance in solving problems.

This work studies the vibration behavior of a gearbox, subject to several rotation conditions, using four lubricant oils with different viscosities. In order of better characterizing the viscosity behavior; oils without any additives were used.

The present study shows that traditional techniques of signal characterization, do not allow characterizing with accuracy viscosities variation. Nevertheless, by the use of some simple procedures of signal processing it was possible to obtain reliable results about the viscosity variation detection.

2.EXPERIMENTAL APPARATUS

The experimental rig is composed by a gearbox manufactured by Cestari which has a reduction factor of 6.32, constituted of two pairs of spur gears as displayed in Fig.1.

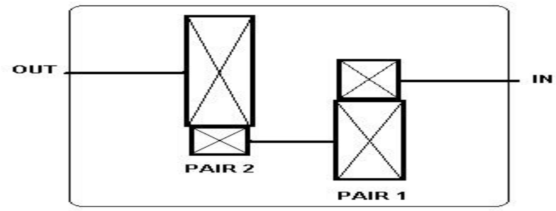

Figure 1 – scheme.

Two piezoelectric accelerometers (bandwidth of 12kHz) are positioned over the box, directly over the first pair of gears, one of them in the vertical direction and the other in the axial direction. The acceleration signals were conditioned, amplified and filtered. For the filtering process it was used two analogical filters (one for each accelerometer) with 10kHz cut-off frequency.

A trigger sensor was also used, each time the output shaft completes a revolution, a photoelectric sensor generates a pulse. This permits not only the shaft speed monitoring but also the use of this signal as a trigger signal. A thermocouple, positioned inside the gearbox in contact with the oil (in the bottom of the gearbox) , allows monitoring the overall oil temperature.

Four paraffinic base oils manufactured by Petrobras (type OB), without additives, were used in the experiments. The oil denominations and the respective viscosities values are described in Table 1.

It worth to point out that for this gearbox, the oil viscosity recommended is 220 cSt.
For each one of these oils it was tested six different shaft speeds in the input shaft of the gearbox (600,800,1000,1200,1400,1600 RPM). The gear mesh frequencies are presented in tab. 2.

Table 1 – oil viscosities

Oil	Viscosity at 40°	Viscosity at 30°
Denomination	cSt	cSt
OB 96	96	170
OB 200	200	330
OB 300	300	550
OB 470	470	900

Table 2 gear-mesh frequencies

Shaft speed (shaft in)		Gear Mesh frequency (Hz)	
RPM	Hz	Pair 1	Pair2
600	10.0	310.0	90.19
800	13.3	413.3	120.25
1000	16.7	516.7	150.32
1200	20.0	620.0	180.38
1400	23.3	723.3	210.44
1600	26.7	826.7	240.51

For each oil and shaft speed, data were collected for two different temperatures: about 40° C (named hot oil condition), which is the working temperature, and about 30 ° C (named cold oil condition). As the time duration of each signal is about 2 s, one can consider that the overall temperature of the gearbox oil remain unchanged during this period.

Nine samples of acceleration signals (both axial and vertical) were acquired for each oil condition, rotation, and temperature. Each signal was digitalized with a sampling frequency of 21 kHz and a total of 42.900 points. No external torque was applied to the gearbox.

3.TRADITIONAL METHODS OF ANALYSIS OF VIBRATION SIGNAL

3.1 RMS

The RMS value is related to the energy of the signal. It is common in industry to use RMS as an important vibration characteristic. In many cases the appearance of one defect are directly detected by the increase of the vibration level of the machine. This means that RMS calculated in a certain frequency band can be used for detection of a defect. The results of RMS can be compared with normalized values or even with values previously collected. The RMS value is calculated in the following way:

$$RMS = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - m\right)^2} \qquad (1)$$

3.2 Kurtosis

Kurtosis is defined as the fourth statistical moment, normalized by the standard deviation to the fourth power, which is shown below.

$$K = \frac{1}{N\sigma^4}\sum_{i=1}^{N}\left(x_i - m\right)^4 \qquad (2)$$

Kurtosis represents a measure of the flattening of the density probability function near the average value. A well-known value of the Kurtosis for the normal distribution is 3.

3.4 Power Spectral Density (PSD)

The power spectral density of a discrete-time signal vector is calculated, using Welch's averaged modified periodogram method (Proakis, 1996) . The signal is divided into overlapping sections, each of which is detrended, then windowed by a Hanning window parameter, then zero-padded to a specified length. The squared magnitude of the Discrete Fourier Transform of these sections is averaged to form power spectrum density vector. In this work all the PSD were calculated with a Hanning window of 10500 points, with no overlapping sections and a linear detrend. This leads to a 3 Hz frequency resolution.

4. AVERAGE SIGNAL PROCESSING.

One of the most important steps for signal processing is to grant that the acquired signal accurately represents the physical phenomena that are being observed. That means to minimize information that is non repeatable, and to maximize the one that characterizes the phenomena.

One way of doing that is to average many signals acquired from the same experimental condition. The average will eliminate random noise while the repeatable information is maintained.

Two averaging techniques were used for comparison purposes:

1. Technique A-Without considering averages in the time.

The first used technique does not consider the signal of the trigger. Statistical signal parameters such as RMS, skewness, kurtosis as well as other like the PSD were calculated for all the signal and samples. The representative values considered for a specific experimental condition, is the arithmetic average among all the parameters (including the spectrum) at the same experimental conditions. That means that in this technique it is not done the average of the signal itself , just the average among its characteristics.

2. Technique Tm-Considering time averages.

In this case, it was used the trigger signal to perform time averages (synchronous time average). of the signal. Each averaged signal considers an integer number of shaft revolution. As the shaft speed increases and the acquisition time remains the same, the number of considered used shaft revolution also increases according to tab-3.

Table3-Number of considered turns for shaft speed.

Shaft in (RPM)	Number of turns considered
	For sample
600	2
800	3
1000	4
1200	5
1400	6
1600	7

For each time averaged signal it was calculated the RMS, kurtosis, skewness and the PSD.

The two considered methods tend to eliminate random noises, the average time method (technique Tm), however, should eliminate noises that does not depend of the angular position of the shaft and should point out effects that are related to specific positions of the gears (for instance: the gear mesh frequencies) (Wismer 1997).

5.RESULTS OBTAINED WITH THE TRADITIONAL PROCESSINGS

5.1 Kurtosis

Figure 2 shows the kurtosis (technique A) as a function of the shaft speed. The values presented correspond to results obtained for all the oils in the two temperature conditions, and considering only the vertical acceleration signal. Each curve in the graphic corresponds to an oil viscosity. The lower viscosity is indicated by number 1, and the highest by number 8. The greater the number, the higher is the viscosity. One can see that, for this parameter, it is not possible to find an order regarding the viscosities. The same behavior can be observed considering the axial direction and the Tm technique.

The skewness was also calculated, but the results were also unable to detect viscosity differences.

.

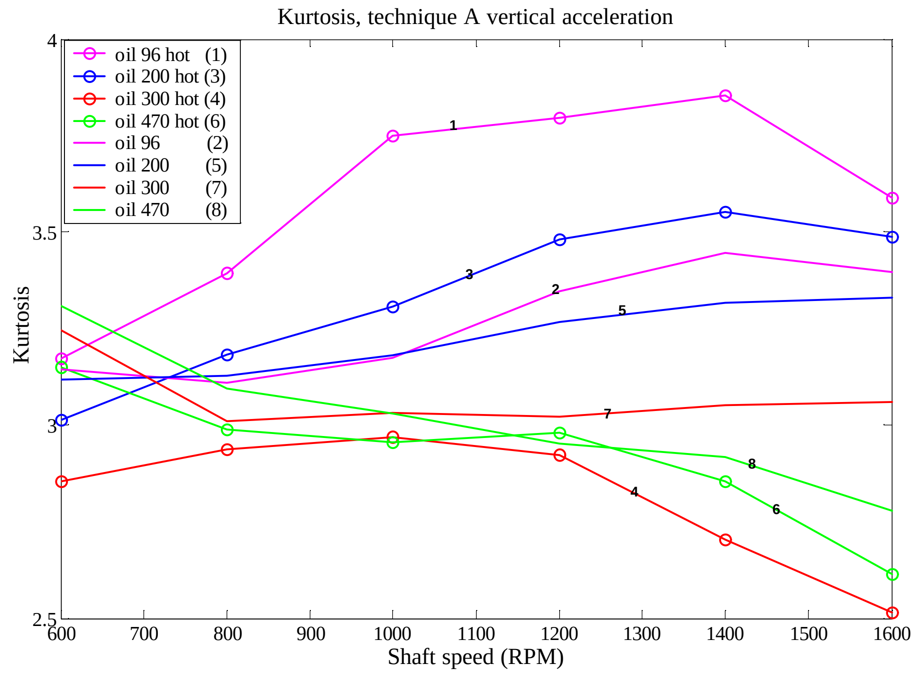

Figure 2- kurtosis technique A vertical (the numbers indicates the viscosity increase)

5.2 RMS

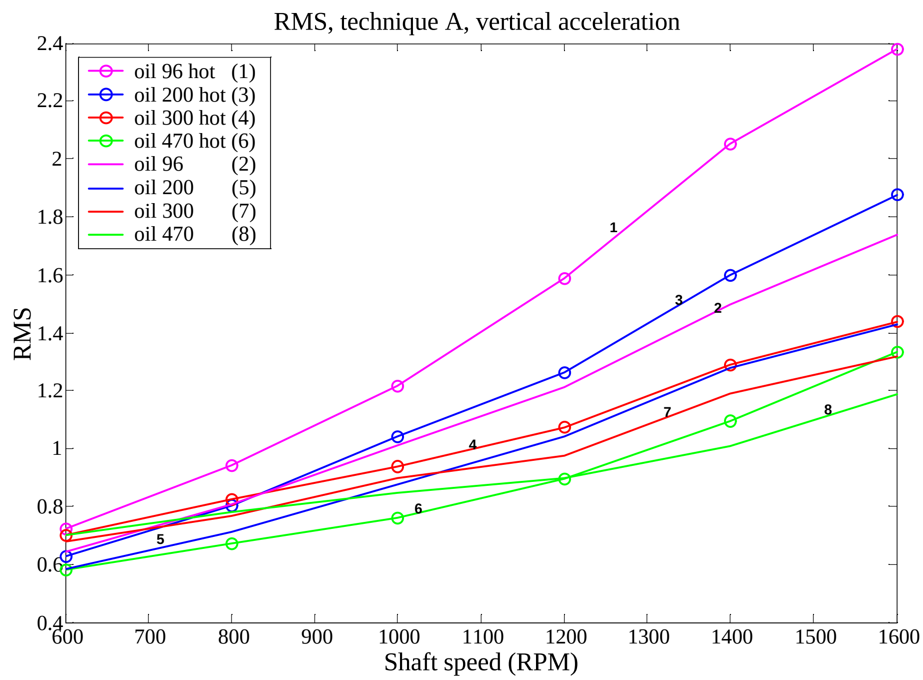

Fig 3 RMS Technique A , vertical vibration (the numbers indicates the viscosity increase)

Figure 3 shows RMS (technique A) as a function of shaft speed The values presented correspond to results obtained for all the oils in the two temperature conditions, and considering only the vertical acceleration signal.

It can be seen that there is a general tendency of increasing the RMS with the shaft speed rising, what is expected. The higher the speed, the higher is the general vibration level (Almeida 2001).

At higher shaft speed, the heating of the oil causes an increase of the RMS value. At low shaft speed this behavior also happens with the exception of the oil with the higher viscosity (470).

It is important to point out that the decreasing of oil viscosity does not always corresponds to an increase of the global vibration level (for instance: curves 6 and 8).

6. PROPOSED VISCOSITY CHARACTERIZATION METHODOLOGY

Figure 4 presents the vibration spectra of the vertical vibration signal for different oil viscosities at 1000 rpm shaft speed. Carefully observing these spectra it is possible to note that in the frequency band from 2000 to 7000 Hz, the higher are the peaks the lower is the viscosity, although this band contains low energy level (very low PSD values), compared to other bands.

In order to point out this fact, the spectrum was separated in three frequency bands:

· Band 1 (B1) - 0 to 2000Hz
· Band 2 (B2) - 2001 to 7000Hz
· Band 3 (B3) - 7001 to 10000Hz

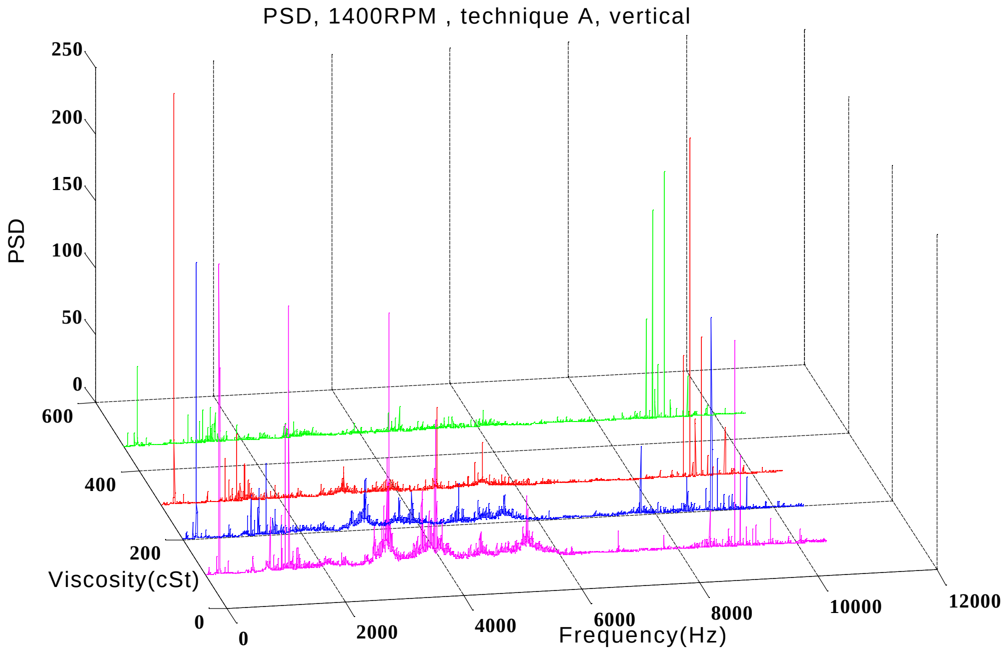

Figure 4 – PSD technique A vertical 1000 RPM

For each one of these bands, considering all the experimental conditions, it was calculated the integral of the spectrum. That corresponds to the RMS of the signal in that frequency band. These parameters, calculated for each one of the three bands, are named respectively: ipsdB1, ipsdB2, ipsdB3.

Figures 5, 6 and 7 represent respectively the integral for the bands B1, B2 and B3, in a logarithmic scale, as a function of shaft speed.

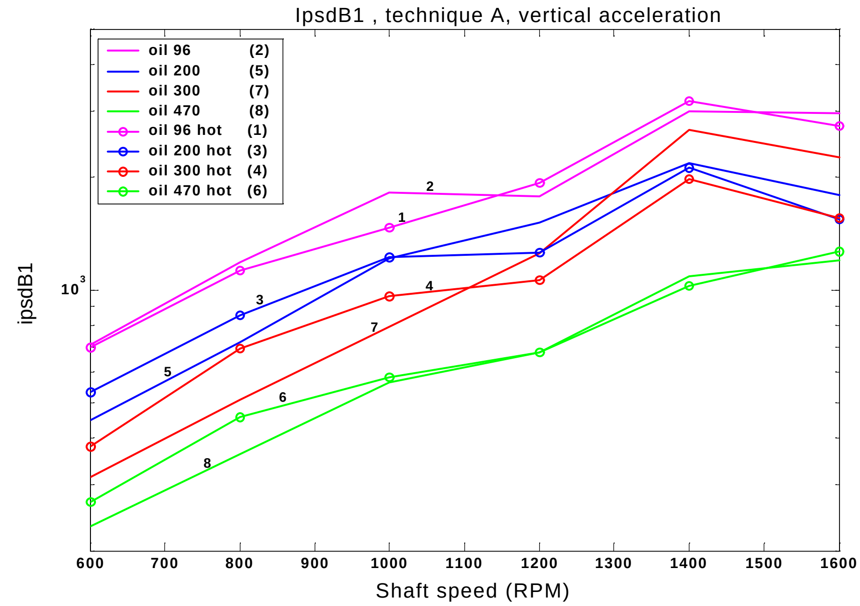

Figure 5 –IpsdB1 ,technique A, vertical (the numbers indicates the viscosity increase)

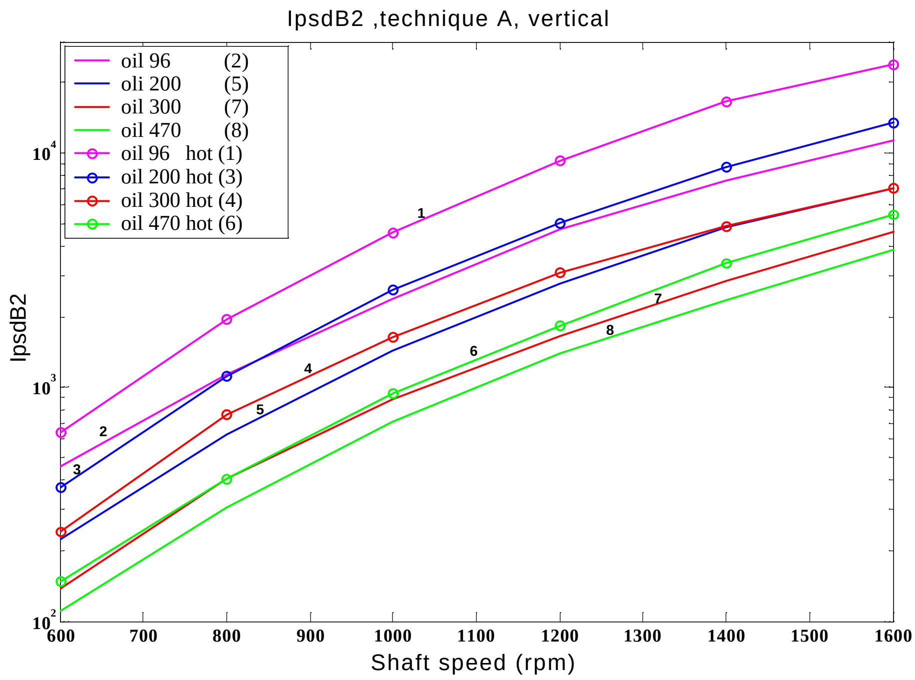

Figure 6 –IpsdB2, technique A , vertical (the numbers indicates the viscosity increase)

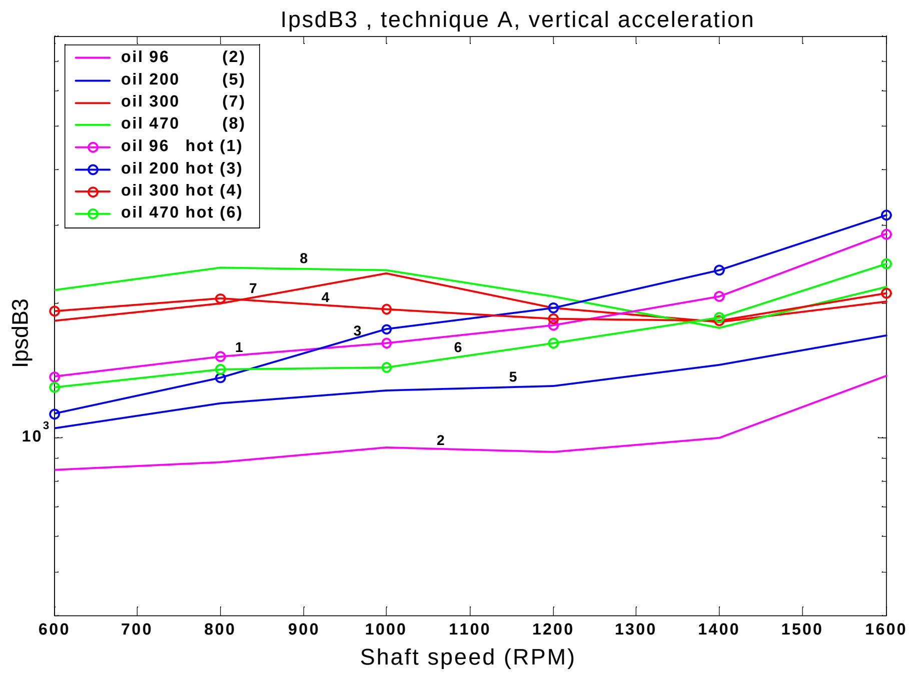

Figure 7-IpsdB3, technique A, vertical (the numbers indicates the viscosity increase)

It is clear, by the analysis the graphics above that, in band 2, data appear perfectly ordered as a function of the viscosity, as noted by the indicative numbers at the curves. Additionally, due to the logarithmic scale, one can observe the tendency for equally spaced curves for all shaft speeds.

Despite the different nominal viscosities, the oil 96 cold (2) and oil 200 hot (3) have approximately the same viscosity, due to their different temperatures. As can be seen in Figure 6, the results show this behavior. That means that the proposed method is connected with the viscosity value, showing the same value for different oils with the same viscosity.

It is also possible to observe that this fact can not be seen in any other of the considered bands and neither in the graph corresponding to the whole spectrum (Figure4).

Regarding the Tm average method the results were the same when concerning vertical acceleration data. For axial acceleration signals the results were not as good as those.

7.CONCLUSION

Observing the whole spectrum of the signals it is difficult to note any consistent and regular spectra behavior as a function of the oil viscosity.

The variation of the oil viscosity does not alter, in a significant and repetitive way, the skewness and the kurtosis of a vibration signal. Since these parameters are correlated to the probability density function (pdf) of a signal, it can be said that the viscosity variation does not implicate in changes in the pdf form. Therefore, these parameters are not useful to distinguish lubricants viscosities changes.

RMS values have led to better results than the parameters previously mentioned, but only for higher shaft speeds .

It is possible to see the influence of the viscosity variation in the frequency band from 2000 to 7000Hz (B2), even if this band has a lower energy level compared to the remaining bands of the PSD.

In all tested conditions, one can clearly separated the viscosity effects, using the proposed parameter defined as the integral of the spectrum in this band (B2). This parameter decreases with the rising of the viscosities, for all shaft speed.

The use of the synchronous time average leads to the same conclusions, but with worse results.

The axial acceleration has shown, for this purpose, results much worse than those vertical one.

All these conclusions indicate that vibration analyses can be a useful tool for lubricant condition monitoring. Further studies using contaminated and additivated lubricants, extending the knowledge on the subject, will be able to confirm the reliability of the proposed methodology for lubrication condition monitoring.

7. ACKNOWLEDGMENTS

The authors whishes to thanks to FAPESP for the financial support. (Process 01/06070-3).

We wish to thank Cestari Industrial e Comercial SA for supplying us with a gearbox and material. We also wishes to tanks to the Engineers Bruno Righi from Petrobras , Carmem Almeida and Luiz Wanderley Bratfish Pace, from Buckman laboratories, for supplying the oils and materials and to Engineer Alex Righi from Engefiltro for the ideas and materials.

8. REFERENCES

Almeida , R G ; Vicente , A S ; Padovese, L R; 2001, New Technique For Evaluation of Global Vibration Levels in Rolling bearings, Anais do Cobem 2001.

Boes, D. C.; Graybill, F. A.; Mood, A. M.; 1974, Introduction to the Theory of Statistics, 3rd. Ed., McGraw-Hill.

Dorinson, A ; Ludema, K; 1997, Mechanics and Chemistry in Lubrication; Tribology series , 9 , Elsevier 1985.

Pachaud, C.; Salvetat, R.; Fray, C.; Crest Factor and Kurtosis Contributions to Identify Defects Inducing Periodical Impulsive Forces, Mechanical Systems and Signal Processing, June, , pages 903-916.

Proakis, J.G; Manolakis, D.G.; 1996, Digital Signal Processing, 3rd Ed., Prentice Hall.

Silva, A.; 1999, "Detecção e Análise Dinâmica de Falhas em Rolamentos" ; Tese de Doutorado, EESC-USP.

Tandon, N.; Choudhury, A.; 1999, A Review of Vibration and Acoustic Measurement Methods for the Detection of Defects in Rolling Element Bearings; Tribology International, Vol.32, May , pages 469-480.

Taylor, J I; 2000, The Gear Analysis Handbook, VCI editors, United States.

Wismer, N J; 1997, Time Domain Averaging Combined With Order Tracking; Bruel and Kjaer application Notes

Su, Y T ; Sheen Y T ; Lin M H 1992; Signature Analysis of roller bearing vibrations: lubrication effects ; Journal of mechanical engineering science , Vol. 206